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APGC-TDR-62-35

Study of Target Penetration Prediction by High-Speed and Ultra-High-Speed Ballistic Impact

(Third Quarterly Report, 1 January - 31 March 1962)

APGC Technical Documentary Report No. APGC-TDR-62-35

MAY 1962 • AFSC Project 9860

DEPUTY FOR AEROSPACE SYSTEMS TEST

AIR PROVING GROUND CENTER

AIR FORCE SYSTEMS COMMAND • UNITED STATES AIR FORCE

EGLIN AIR FORCE BASE, FLORIDA

(Prepared under Contract No. AF 08(635)-2155 by the Hayes International Corporation, Birmingham, Alabama)

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FOREWORD

This report was prepared under Contract AF 08(635)-2155, "Study of Target Penetration Prediction By High Speed and Ultra High Speed Ballistic Impact", AFSC Project 9860. Work was administered under the direction of APGC (PGWRT), Eglin AFB, Florida, with Mr. A. G. Bilek as Project Engineer.

Catalog cards with abstracts may be found in the back of this document.

ABSTRACT

Complete results of the preliminary statistical analysis, which were partially reported in the previous quarterly report, are reported herein. This statistical correlation, based on all hypervelocity terminal ballistic data gathered prior to December 1961, attempts to relate the depth of penetration in semi-infinite targets with ten independent variables. Without any initial assumptions being made regarding the process of ballistic impact or the shape of the craters formed, this analysis produced an equation quite similar to the empirical equation used by many investigators to fit their data.

Also reported are initial attempts to formulate a theoretical model for the purpose of testing accumulated experimental data. This theoretical model is developed from a consideration of energy conversion during impact.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Morrill E. Marston

MORRILL E. MARSTON
Colonel, USAF
Deputy for Aerospace Systems Test

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LIST OF SYMBOLS

P_c	crater depth measured from original target surface
D_c	crater diameter at original target surface
V_c	crater volume below original target surface
D_p	projectile diameter
ρ	density
v	impact velocity
c	dilatational wave velocity in a given material
m	mass
T	target temperature
V	volume
p	pressure
A	area
t	time
E	energy
ϵ	strain
Y	yield point
U	ultimate strength (tensile)
L	latent heat of fusion

SUBSCRIPTS

t	target
p	projectile
c	crater
o	STP conditions or arbitrary reference point

INTRODUCTION

The purpose of this study is to gather and assemble existing data on ballistic impact and on material failure, especially at high impact velocities or large loading - to establish the relative importance of such factors as projectile velocity, mass, sectional density, projectile/target contact areas, etc., and to use this information to deduce the mathematical relationships of critical factors as the target structure responds to impact and is penetrated.

Existing experimental data relative to ballistic impact at high velocities are being evaluated on a statistical basis through the use of an RPC 4000 digital computer. The general form of the statistical approach was outlined in the First Quarterly Report[1]. A preliminary analysis of the correlation between depth of penetration and ten independent variables was reported in the Second Quarterly Report[2] and will be discussed more fully in this report.

In addition, the general areas of ballistic impact and material failure are being investigated in order to develop relationships which may be tested against existing experimental data. Some general aspects of target behavior under ballistic impact were discussed in the Second Quarterly Report and some justification was given for the use of static or quasi-static material parameters in the initial statistical analysis.

EMPIRICAL MODEL

The initial approach to the empirical model was a statistical analysis of the factors influencing the depth of penetration (P_c) in semi-infinite* targets. Penetration depth was considered a function of ten independent variables according to the equation

$$P_c = k_0 \, v^{k_1} \rho_t^{k_2} \rho_p^{k_3} V_p^{k_4} T^{k_5} Y_t^{k_6} Y_p^{k_7} C_t^{k_8} U_t^{k_9} D_p^{k_{10}} .$$

This equation was reduced to its associated linear form

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* Semi-infinite according to the rule-of-thumb published by Kinard, et al[3], that the penetration is no greater than 20% of the target thickness.

$$\log P_c = \log k_0 + k_1 \log v + \ldots\ldots\ldots\ldots\ldots\ldots + k_{10} \log D_p$$

and the method of least squares was used to determine a "best" set of values for the variable exponents (coefficients) k_i based on minimizing the value of

$$\sum_{i=0}^{10} \left[\log (P_c)_{\text{experimental}} - \log (P_c)_{\text{calculated}} \right]^2 .$$

The independent variables were dropped one-by-one starting with D_p and the effect on the k_i is summarized in Table I.

After the k_i were computed, various statistical tests were made to determine the validity of the results obtained. The per cent of the variance in the log of dependent variable (P_c) that is explained by the logs of the independent variables is given by the multiple correlation coefficients listed in Table I. The significance of these multiple correlation coefficients was discussed in the previous progress report[2]. An analysis of this variance using the F distribution tests the null hypothesis that all β_i are zero. Separate tests of the individual hypothesis $\beta_i = 0$ were made using the t distribution. Variables corresponding to the β_i that were not significant by the preceding test were then removed and separate tests were made on each of the removed variables to see whether the adding of this variable improved the fit. Individual correlation coefficients between all independent variables were also calculated.

The significance of the target yield strength above many of the other variables contributing to the multiple correlation coefficients was noted in the previous progress report. However, the target yield strength (Y_t), the dilatational wave velocity in the target (C_t), and the target ultimate strength (U_t) are statistically indistinguishable as evidenced by the fact that the calculated individual correlation between them is over 95%. The diameter of the projectile (D_p) is also statistically indistinguishable from the volume of the projectile (V_p) so that the effect of dropping (D_p) should be insignificant. With the exception of the above correlations and the dependence of C_t on ρ_t, the rest of the individual correlation coefficients show a low degree of interdependence.

The close correlation between D_p and V_p and between U_t, Y_t, and C_t confuses the k_i calculated in the first three lines of Table I. It is interesting to note that that the last line of the table yields

$$P_c = .009 \quad v^{.776} \rho_p^{1.24} \quad V_p^{.338} \qquad (1)$$

Table I. The empirical coefficients k_i in the equation

$$P_c = k_o \, v^{k_1} \rho_t^{k_2} \rho_p^{k_3} V_p^{k_4} T^{k_5} Y_t^{k_6} Y_p^{k_7} C_t^{k_8} U_t^{k_9} D_p^{k_{10}}$$

k_o	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9	k_{10}	Multiple Correlation Coefficient
10^{-9}	.988	.028	.997	-.039	.241	-.094	.067	2.27	-.893	2.33	.961
10^{-11}	.979	.157	1.01	.372	.217	-.131	.069	3.10	-1.11		.957
10^{-5}	.975	-.228	1.03	.354	.180	-.552	.053	.909			.950
10^{-3}	.961	-.461	1.10	.353	.331	-.354	.078				.949
10^{-3}	.987	-.447	1.07	.345	.568	+.354					.945
10^{-4}	.845	-.061	1.18	.340	.594						.875
.009	.776	-.044	1.24	.388							.870

with ρ_t being statistically insignificant according to the t distribution. This is in good agreement with the many investigators[4,5,6,7,8,9,10,11] who found empirically, that the volume of the crater is proportional to the projectile kinetic energy

$$V_c = k \left(\tfrac{1}{2} \rho_p V_p v^2\right) \qquad (2)$$

coupled with the observation[7,8,11,12,13,14] that the craters formed are hemispherical

$$V_c = \frac{4}{3} \pi P_c^3 \qquad (3)$$

since these two observations yield an equation of the general form

$$P_c = k' v^{\frac{2}{3}} \rho_p^{\frac{1}{3}} V_p^{\frac{1}{3}} \qquad (4)$$

The agreement in the exponents of v and V_p between equations (1) and (4) is quite good. However, the disagreement between the exponent of ρ_p is quite substantial. Palmer[15] points out that all Utah cratering studies seem to best fit an equation similar to equation (4) in which the exponent of ρ_p is $\frac{1}{2}$, but this does little toward resolving the disagreement. Since the multiple correlation coefficient shows that 87% of the variance in (P_c) may be explained by the variance in v, ρ_p, and V_p, it is not surprising that equation (4) has been quite successful in fitting individual experimental data.

Palmer[15] observes that the empirical crater depth seems to be inversely proportional to the $\frac{1}{3}$ power of the target shear strength and Eichelberger[11] observes that it seems to be inversely proportional to the $\frac{1}{3}$ power of the target Brinell hardness. Both the Brinell hardness and the shear strength are quite closely correlated with the yield strength, and lines 4 and 5 of Table I indicate a dependence of P_c on either the plus or minus $\frac{1}{3}$ power of the target yield strength.

The preliminary analysis was made on approximately 1200 experimental shots only half of which were reported in enough detail to enable assignment of strength parameters to the target and projectile. Of the resulting 600 shots, only 174 were performed at velocities greater than the bulk wave velocity in the target medium and over 90% of these "supersonic" shots were in lead targets where the bulk wave velocity is quite low (about 5400 feet per second). This analysis, then, seems to indicate that the crater depth can be adequately predicted on the basis of 4 or 5 out of the ten independent variables chosen, at least for impact velocities below the bulk or

dilational wave velocity in the target medium.

A second statistical analysis was attempted during this report period using only the 174 shots at impact velocities above the bulk wave velocity in the target medium. The results of this analysis were completely inconclusive due primarily to the fact that all but 17 of the shots were fired into lead targets. This overwhelming number of lead shots created additional correlation between the various material parameters yielding a spurious set of results. Since this analysis was performed, the results of about 60 shots using aluminum projectiles on aluminum targets at impact velocities between 27,000 and 33,000 feet/second have been received. A new high impact velocity analysis will be initiated soon, subject to the boundary conditions outlined below.

Our empirical analysis to date clearly indicates that we were too concerned with the quantity of experimental data and not enough concerned with quality. An analysis of (P_c/D_p) as outlined in the First Quarterly Report is almost completed on all shots below the bulk wave velocity in the target medium. Before any further analyses are started, the terminal ballistic data will be very carefully screened according to the conditions under which it was taken and care will be exercised in balancing the data to some degree so that a more even distribution of target and projectile materials and impact velocities will be used.

Spurious results caused by the statistical interdependence of independent variables clearly illustrates the need of a theoretical analysis to complement any empirical study. The theoretical model which follows is merely an attempt to develop a logical set of independent variables in dimensionally correct groupings against which to test the experimental data.

THEORETICAL MODEL

In conjunction with a broad statistical study of medium and high speed ballistic impact data, theoretical studies of target response are also in progress. The study is attempting to correlate target behavior with pertinent impact and material parameters through fundamental considerations of both the energy and momentum processes involved.

The mechanics of impact behavior involves a combination of energy absorbing and momentum absorbing processes. In the case of lower velocity impact, the target tends to steadily resist the force of impact, resulting primarily in an energy absorbing process, as the empirical models seem to indicate (V_c proportional to v^2). This is an over-simplification, of course, but the same behavior would be expected to occur at higher impact velocities, although to a lesser degree.

In higher speed impacts the ejection of target particles is more and more in evidence, and it seems apparent that the high momentum of the backsplash material indicates the importance of considering the momentum absorbing processes involved. This would seem to imply that the crater formation in ultra-high speed impact tends to become a closer function of velocity to the first power as the theories of Bjork and Öpik indicate.

The kinetic energy of a projectile impacting a semi-infinite target is transformed through a number of complex processes. For the purposes of obtaining approximate expressions for the principle energy absorbing processes, the projectile kinetic energy can be assumed to be absorbed as follows:

1. Kinetic energy of the material backsplashed during cavity formation

$$E_B = \left(\tfrac{1}{2}\, mv^2\right)_{\text{backsplash}} \qquad (5)$$

Various opinions have been expressed as to the relative magnitude of the kinetic energy of this ejected material. It does appear that the mass of the backsplash material is usually much greater than that of the original projectile. Although the Utah group[15] has measured very high velocities (up to 20 times the impact velocity for micron-sized spray particles), the average velocity of the backsplashed material must be quite small. This is verified by photographs of impacts which show large chunks of material moving backward from the point of impact with very small velocities.

2. Energy required to melt, vaporize or otherwise dissociate projectile and target material during the crater formation. It is considered of little consequence here that the actual mechanism of material separation is at least in part a result of cavitation following the disappearance of the projectile. Bromberg has pointed out that the terminal ballistic data of Summers and Charters[5] can be explained using the heat of fusion.

$$E_L = V_c\, \rho_t\, L_t + V_p\, \rho_p L_p \qquad (6)$$

If any vaporization takes place, it could account for a very large portion of the impact kinetic energy. A simple calculation for an aluminum projectile striking an aluminum target at an impact velocity of 9 km./sec. shows that it would take 1/5

of the impact kinetic energy to vaporize the projectile. If the crater volume were 57 times the projectile volume (not an unreasonable figure) the energy necessary to vaporize the entire crater would be over 10 times the impact kinetic energy. The vaporization term has been eliminated from equation (6) because it appears that only a small portion of the projectile is actually vaporized. To create the spray of micron-size, backsplashed particles being studied by the Utah[15] group would require at least a portion of the vaporization energy, but here again, the total mass of this material is small.

3. Energy emitted as electromagnetic radiation at all wavelengths due to the heat generated at the point of impact. This would be given by the Stefan-Boltzmann Law as

$$E_R = e \sigma T^4 At \qquad (7)$$

where (e) is the emissivity of the target material, (σ) is the Stefan-Boltzmann constant, (T) is the Kelvin temperature, (A) is the area of the emitting surface, and (t) is the time over which this emission takes place. Picking a good value for (T) is quite difficult although, if (A) is assumed to be the crater area, (T) might be approximately the melting temperature of the target material.

Since (T) and (A) will both be functions of time, it might be well to define E_R as

$$E_R = e \int_0^{t_f} T(t)^4 A(t) dt \qquad (8)$$

where (t_f) is the total time of crater development, and try to find reasonable values for the variations of (T) and (A) with time. In any case, this term will probably be small in comparison with some of the other terms.

4. Energy transferred to atomic, molecular, or granular change such as the energy of recrystallization

$$E_A = \text{Undetermined quantity}$$

The Utah[15] group has shown that from 12 to 15% of the energy required to push a lead ball into a lead target quasi-statically goes into recrystallization. It has not yet been determined what independent variables might enter into this term.

5. Strain energy (E_S) absorbed by the solid target material. This can be approximated by an integration involving the product of the strain energy absorbed per unit volume of target material and the volume of target material so stressed.

$$E_S = \int_0^V p \;\epsilon\; dV \qquad (10)$$

An estimate will be required of the portion of the target that is stressed and to what extent it is stressed in finally absorbing a portion of the terminal impact energy. This will require an understanding of the magnitudes of the pressures developed, the pressure-time variations in the target, and the pressure-deformation characteristics (equations of state) of the target material.

The volume integral in equation (10) may be transformed to a time integral by reference to Figure 1.

$$dV = \tfrac{1}{2}\, 4\, \pi\, (ct)^2 \; d\,(ct) \qquad (11)$$

Since the pressure (p) is a function of time and the strain (ϵ) is a function of pressure, equation (10) becomes

$$E_S = 2\pi \int_0^{ct'} p\,(t)\; \epsilon\,(p)\; (ct)^2 \; d\,(ct) \qquad (12)$$

The dilatational wave velocity in the unstressed target material (c) is a constant. Although later stages of the pressure wave may travel through the target material at a greater velocity than (c) due to the previous compression of the target by the wave front, the wave front itself cannot move faster than (c) through the previously unstressed target material. This situation seems somewhat analagous to "choked flow" of fluids. Equation (12) may then be written

$$E_S = 2\pi \int_0^{t'} p\,(t)\; \epsilon\,(p)\; c^3\, t^2 \; dt \qquad (13)$$

The total time (t') during which stress energy acts as a means of removing energy from the point of impact is somewhat in doubt. However, it seems most reasonable to assume that (t') is the time after impact at which the projectile ceases

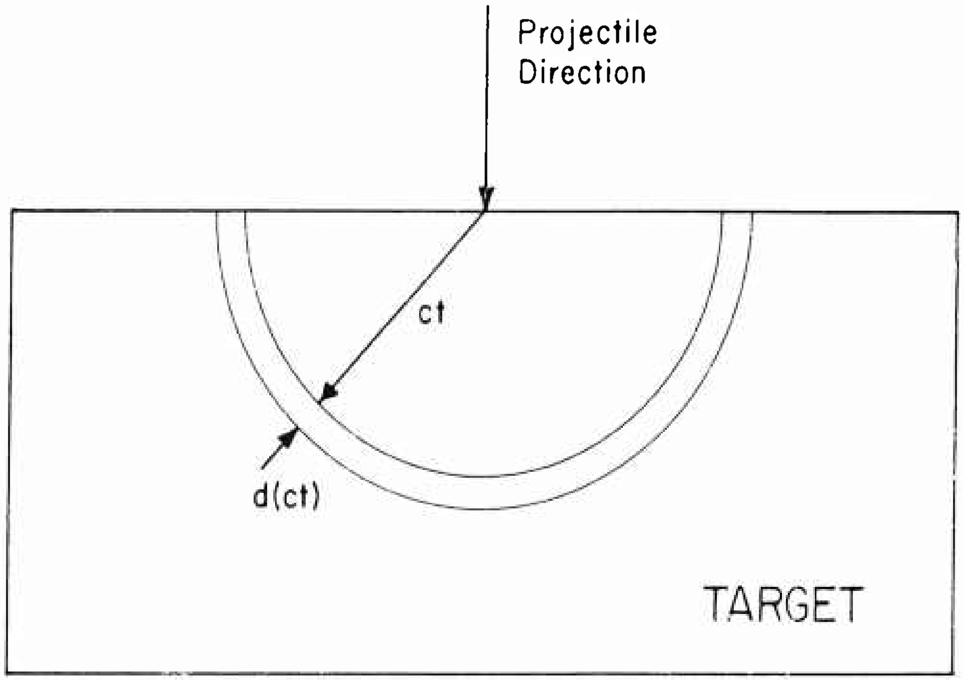

FIGURE 1

be a causitive force in the growing crater. According to Gehring[16] this time will be given by

$$t' = \frac{m_p^{1/3}}{v} \left(1 + \sqrt{\frac{\rho_p}{\rho_t}} \right) \qquad (14)$$

Before the integral of equation (13) can be evaluated, it remains to describe the variation of pressure with time and the variation of strain with pressure over the interval t . Attempts to arrive at a reasonable expression for the pressure variation are underway. Once the pressure variation is known, the variation in the strain may be evaluated from Hugoniots similar to those given by Bjork[17]. It appears that regardless of the pressure variation, the integrated form of equation (13) will be

$$E_S = \frac{2\pi}{K} (c\, t')^3\, p_o\, \epsilon_o \qquad (15)$$

where (p_o) is the maximum pressure applied to the target material, (ϵ_o) is the ultimate strain of the material at pressure (p_o), and K is a constant dependent upon the mode of variation of p(t) and $\epsilon(p)$.

It should be pointed out here, that a portion of the energy which goes into elastic-plastic strain energy may account for part of the backsplashed kinetic energy (equation 5). This would be due to the "decompression wave" tending to push the bottom of the crater backward after the forward pressure has dropped essentially to zero.

Assuming that all modes of energy dissipation have been accounted for in the above five expressions, conservation of energy would require that

$$\tfrac{1}{2}\, m_p\, v_p^2 = E_B + E_L + E_R + E_A + E_S \qquad (16)$$

If the crater volume is assumed to be proportional to the kinetic energy of the projectile, and the shape of the crater is assumed to be hemispherical, an expression for P_c will result. As soon as more thought is given to some of these energy terms and as soon as the experimental data is arranged in a better form statistically, the theoretical expression will be fitted to the empirical data in order to evaluate the constants in the expression and to find the degree to which the variance in P_c or V_c may be explained.

The principle of impulse and momentum requires that the impulse of a force system on a system of particles during a time interval be equal to the change in momentum of the system of particles during the time interval. If the time interval in question is taken to be the time during which the projectile remains as a causitive force (t'), then the impulse of the resulting impulse developed in the target plus any external reaction (R) developed during the time interval can be equated to the difference in the momentum of the ejected particles and the projectile impact momentum.

$$F \Delta t = (m v)_{final} - (m v)_{initial}$$

$$- \int_0^{t'} p A \, dt - \int_0^{t'} R \, dt = (- m v)_{backsplash} - m_p v_p$$

or since (Figure 1) $A = \frac{1}{2} 4 \pi (ct)^2$

$$\int_0^{t'} 2\pi p (ct)^2 \, dt + \int_0^{t'} R \, dt = (m v)_{backsplash} + m_p v_p \qquad (17)$$

Assuming there is no external reaction at the target (R = 0), a ballistic pendulum-type experiment to measure backsplashed momentum might enable the variation of pressure with time to be evaluated for insertion into the energy equation (13).

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Air Proving Ground Center, Eglin Air Force Base, Fla.
Rpt No. APGC-TDR-62-38. STUDY OF TARGET PENETRATION PREDICTION BY HIGH SPEED AND ULTRA HIGH SPEED BALLISTIC IMPACT. [illegible] 2.14 p. incl illus., tables, 17 refs.
Unclassified Report

Complete results of the preliminary statistical [illegible] partially reported in the previous quarterly report [illegible] This statistical correlation [illegible] all [illegible] [illegible] attempt [illegible] penetration in semi-infinite targets [illegible] fundamental assumptions [illegible] shape of the craters [illegible] depth of [illegible] equations quite similar to the empirical equations used by many investigators to fit their data. Also, reported [illegible] attempts to formulate a theoretical model for the purpose [illegible] accumulated experimental data. This theoretical model is developed from a consideration of energy conversion during impact.

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